APPENDIX C

RADIOACTIVE SOURCE CONSIDERATIONS IN NUCLEAR FACILITY DESIGN

C- 1. Radiation sources

Radiation sources encountered in facilities which produce or use radioactive materials may be generally divided into four generic types including radioactive waste, radioactive components, radioactive contamination, and test and radiographic sources.

a. Radioactive Waste. Facilities using radioactive materials can generate liquid and or solid wastes. In addition, accelerator facilities are also capable of generating waste. If the waste is liquid, there may be collection and holding tanks where the liquid is held for sampling, for delay until decay reduces the radioactivity levels, or for storage prior to solidification. These tanks would be radiation sources. There can be packaging areas for solidified liquid waste and other solid wastes where final preparations are made for the shipment of radioactive waste. If the solid waste is not shipped immediately, a waste storage area will be required. These areas would also be sources of radiation.

b. Radioactive Components. The numbers and types of components in a facility which may contain radioactive material and therefore be a source of radiation will vary greatly from facility to facility. Typical components would include:

(1) Pumps.
(2) Valves.
(3) Heat exchangers.
(4) Filters and filter housings.
(5) Vessels and tanks.
(6) Vent ducts.
(7) Connecting piping.

c. Radioactive Contamination and Activation. Any areas of a facility which are contaminated with radioactive materials will be sources of radiation. Contamination can occur by contact with unsealed radioactive materials entrapment. Exposure of structural materials to emitted radiation can result in those materials becoming radiation sources themselves. In this case direct contact with radioactive source material is not required; exposure to the emitted radiation is the activating mechanism. For example, reactors and high energy accelerators, particularly those resulting in the production of high energy neutrons, pose particular problems of this nature. Typical affected areas would include:

(1) Laboratories.
(2) Maintenance and manufacturing areas.
(3) Decon areas.
(4) Storage areas.
(5) Test areas.
(6) Reactor containment.
(7) Accelerator room.
(8) Medical treatment areas.

d. Test and Radiographic Sources. Low radioactivity sources will be present at every facility to check for the proper operation of radiation monitoring instrumentation. Additionally, higher radioactivity sources may be present in some facilities to permit calibration of radiation monitoring instrumentation. These sources may emit alpha, beta, gamma, or neutron radiation. They may be sealed, partially sealed, or unsealed in form (para C-3). If radiography is performed at a facility, sealed radiation sources will be present.

C-2. Half-life considerations

Approximately 2,000 nuclides have been identified. Of these, some 235 are stable, nonradioactive; some 44 occur in nature as radioactive nuclides; and the remainder of the nuclides, over 1,700, are artificially, man-made, radioactive. Each radioactive nuclide, man-made or naturally occurring, has a property called half-life which is defined as the time required for half the atoms of a radionuclide to disintegrate to another nuclear form. This new nuclide form is usually stable (nonradioactive) but, for some nuclides, the new nuclide may also be radioactive. The half-lives of radionuclides range from a fraction of a second to millions of years. The approximate half-life of some commonly encountered radionuclides are listed in the following table taken from the "Radiological Health Handbook."

Radionuclide	Half-Life	Radionuclide	Half-Life
N-16	7.13 sec.	H-3	12.30 years
Xe-133	5.27 days	Cs-137	30 years
I-131	8.05 days	Am-241	458 years
Fe-59	45.00 days	Ra-226	1602 years
Ir-192	74.20 days	C-14	5730 years
Mn-54	313.00 days	Pu-239	24390 years
Pm-147	2.62 years	U-235	7.1×10^8 years
Co-60	5.26 years	U-238	4.51×10^9 years
Kr-85	10.76 years		

a. Calculation of Residual Concentration of a Single Radionuclide Source. The effect of radioactive decay, particularly for shorter half-life radionuclides, may be to reduce or eliminate levels of contamination and radiation exposure prior to decommissioning activities. For example, seven half-lives of decay will result in less than one percent of the original radioactivity of a radionuclide. The concentration of any radionuclide following a period of decay can be calculated using equation C-1.

$$C = C_0 \exp(-\lambda t) \qquad \text{(eq. C-1)}$$

where: C_0 = The initial concentration

λ = The decay constant = 0.693/half-life (units are in time-1)

t = The decay period in half-life units of time; (the time units for "λ" and "t" must be the same)

C = The concentration following decay period "t"

From this equation the remaining concentration has been calculated for several decay periods and are given in the following table:

Decay Period (in half-lives)	Reduction Factor (%)	Fraction of Original Concentration Still Remaining
3.32	90.0	0.1
6.64	99.0	0.01
9.96	99.9	0.001

For example, if the objective of a SAFSTOR program is to provide a 99-percent reduction in a colbalt-60 contaminant, the SAFSTOR period would be calculated as follows:

SAFSTOR period = (decay period)(half-life) (eq. C-2)

Where: decay period = 6.64 half-lives (99% reduction)

half-life = 5.26 years/half-life (cobalt 60)

or

SAFSTOR period = (6.64)(5.26) = 35 years

This reduction in the concentration of a given radionuclide due to radioactive decay is graphed in figure C-1.

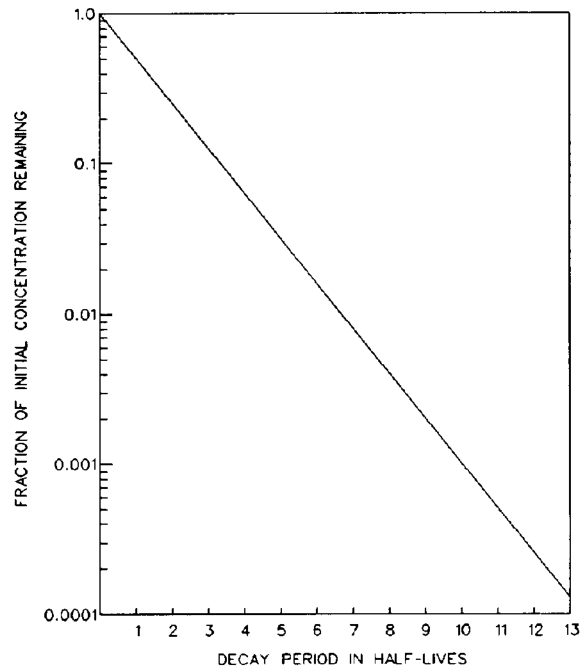

Figure C-1. The Reduction In The Concentration Of A Radionuclide Due To Radionuclide Decay.

Note that this plot represents the values indicated in columns 1 and 3 of the table above. It should be noted that the above discussion represents a situation where the radionuclide of interest is not part of a decay chain; that is, it does not result from the decay of another radionuclide. However, when a decay chain is involved, the radionuclide of interest (daughter product) is being increased in concentration, while it decays, by the decay of another radionuclide (parent radionuclide). Depending on the half-lives and initial concentrations of the parent and daughter radionuclides, it is possible that the concentration of the daughter product will increase for some period of time after primary production method (e.g., fissioning) for these radionuclides has stopped. The concentration of the daughter product in a parent-daughter decay chain following a period of decay is calculated using equation C-3.

(eq. C-3)

$$C_d = C_{do}\exp(-\lambda dt) + \frac{C_{po}\lambda_d}{\lambda_d - \lambda_p}(\exp(-\lambda_p t) - \exp(-\lambda_d t))$$

Where: C_{do} = The initial concentration of the daughter radionuclide

C_{po} = The initial concentration of the parent radionuclide

C_d = The concentration of the daughter following decay period t

λ_d = The decay constant for the daughter radionuclide

λ_p = The decay constant for the parent radionuclide

t = The decay period

b. Composite Radionuclide Source. The presence of only a single radionuclide during a decommissioning is a special case. Usually, several radionuclides would be involved. For the typical case of a composite radionuclide source, selection of a period of deferred decommissioning could be based on various considerations. Presented in figure C-2 is a graphic representation of the total dose rate and its major constituents as a function of the period of radioactive decay. This figure shows that after 2.5 years, all short-lived contributors have decayed out and the total dose rate is due strictly to the radionuclide, cobalt-60. A 90 percent reduction in the total dose rate is achieved after *4.5* years of decay, while an additional 90 percent reduction in the total dose rate would require an additional 17.5 year period of radioactive decay. Either total dose rate or total radioactivity inventory can be represented in the manner shown in figure C-2. Such a graphic representation would be useful in determining the duration of the deferred decommissioning. Again, the case presented in figure C-2 does not involve a decay chain. However, the approach presented would still be valid if a decay chain were involved.

C-3. Containment or sources

Radioactive sources can be classified by the type of containment provided to the material when in normal use or storage. This includes sealed, partially sealed, and unsealed sources. In general, the less containment provided radioactive materials in normal operations, the greater the risk of contamination.

a. Sealed. Sealed sources have the radioactive material contained in a sealed enclosure, usually fabricated from metal. This sealed enclosure permits emissions without concern for the release of radioactive material and subsequent contamination. Sealed source enclosures are inherently secure, but can be breached by mechanical damage such as severe abrasion, impact, or crushing. Sealed sources are used in a variety of applications such as industrial radiography, medical radiation therapy, and radiation monitoring instrument calibration. Sealed sources may be placed in a permanent storage area but require shielding protection to reduce radiation exposure while in transport and storage.

b. Partially Sealed. The radioactive material in a partially sealed source is contained in a manner which prevents the spread of radioactive material during normal handling of the source, but is not sufficient to provide protection if the source is mishandled. For example, alpha and weak energy beta sources are usually covered by a thin mylar sheet. This covering prevents the spread of radioactive material unless the mylar is torn.

c. Unsealed. Unsealed radioactive material can be easily spread if handled improperly. Such material can be

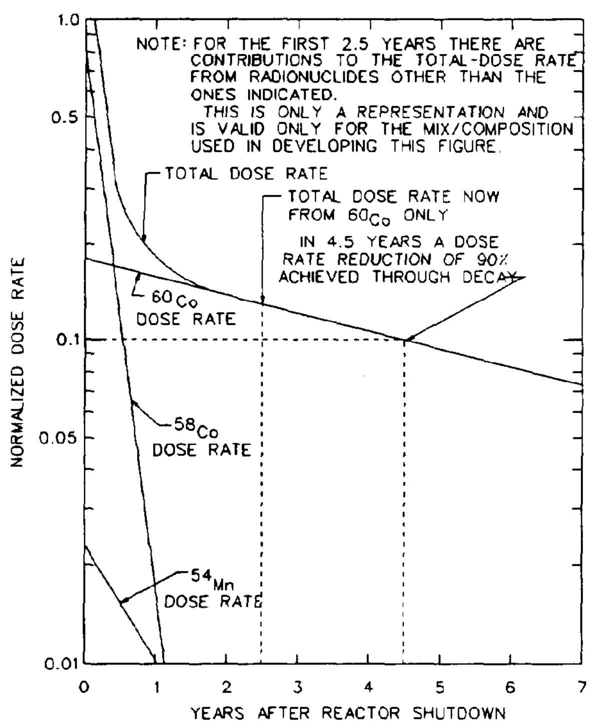

Figure C-2. Reduction Due To Radioactive Decay In The Total Dose Rate From A Composite Radiation Source Term.

liquid, gas, powder, or solid form and, when spread, anything contacted by them becomes contaminated.

C-4. Specific DOD facilities which have radioactive sources

a. Research Laboratories. Depending on its mission, a research laboratory may be involved in a wide variety of activities such as the analysis of material activation by neutrons, the study of radiation exposure effects, and the use of radioactive tracers in experiments. Various radionuclides may be used in a typical laboratory environment or may be used in closed, shielded cells to protect personnel from radiological hazards. Reactors or particle accelerators may also be used at such facilities.

(1) Types of Radiation Expected Depending on the facility mission, a number of different radionuclides may be used. Alpha, beta, and gamma emissions can be expected.

(2) Types of Sources Present. Sealed, partially sealed, and unsealed sources can be expected to be used.

(3) Radioactive Contamination Potential. There is a high potential for contamination in any area of a laboratory where unsealed sources are used in experiments and studies.

(4) Radioactive Waste Generated Moderate to large volumes of solid radioactive waste can be expected. Small to moderate volumes of liquid radioactive waste will be generated.

(5) Potentially Contaminated Areas. Areas of potential contamination include the following:

(a) Laboratory areas (bench tops, fume hoods, glassware, hot cells).

(b) Animal cage areas.

(c) Solid radioactive waste handling and packaging area.

(d) Liquid radioactive waste system (tanks, pumps, valves, piping).

(e) Ventilation system (ducting, filters, filter housings).

b. Medical Facilities. Medical facilities perform a variety of diagnostic and therapeutic procedures using radioactive materials and radiation producing machines. For diagnostic procedures, radioactive material may be injected into a patient in liquid form or taken orally. Radiation producing machines such as X-ray units and Computer Aided Topography (CAT) scanners may be used. For therapeutic procedures, radioactive material may be injected into a patient in liquid form, taken orally, or implanted in solid form (and later removed). High radioactivity cobalt-60 units and linear accelerators (para C-4.e) are also used for radiation therapy.

(1) Types of Radiation Expected Beta and gamma radiation can be expected to be used.

(2) Types of Sources Present. Sealed, partially sealed, and unsealed sources can be expected to be used.

(3) Radioactive Contamination Potential. There is a high potential for contamination where unsealed sources are used for diagnosis or therapy. There is a low potential for contamination when sealed sources are implanted unless the sources are mishandled. There is no potential for contamination from properly utilized sealed sources, such as cobalt-60 units, or from low energy radiation producing machines such as X-ray units or accelerators operating below 10 MeV. Contamination potential is increased for units operating at higher energy levels.

(4) Radioactive Waste Generated Small to moderate volumes of solid radioactive waste can be expected. Small to moderate volumes of liquid radioactive waste will be generated.

(5) Potentially Contaminated Areas. Areas of potential contamination include the following:

(a) Laboratories where liquid sources are prepared for use.

(b) Operating rooms where sources are implanted.

(c) Rooms where patients who have been administered radioactive materials are located.

(d) Solid radioactive waste handling and packaging areas.

(e) Liquid radioactive waste system (tanks, pumps, valves, piping).

(f) Areas where liquid radioactive sources are stored prior to preparation for administration.

c. Fast Burst Research Reactors. A fast burst reactor is an air cooled assembly used to produce a quick burst of fast neutrons and gamma radiation. The radiation bursts are used to simulate nuclear weapons effects for the evaluation and testing of materials and systems.

(1) Types of Radiation Expected From the reactor, primarily gamma and neutron radiation is expected. Irradiation of the test items or reactor structure will cause neutron activation and result in beta and gamma radiation.

(2) Types of Sources Present. The reactor utilizes a sealed source of uranium fuel and fission products. Activated material or test items can be present and would be classified as partially sealed sources.

(3) Radioactive Contamination Potential. In general, the potential for contamination outside the containment structure due to spread of the reactor material is low unless the containment structure becomes damaged. Contamination potential becomes high if the fuel containment fails. The potential for neutron activation of test items or the structure surrounding a reactor is high.

(4) Radioactive Waste Generated No radioactive waste is expected at this type of facility.

(5) Potentially Contaminated Areas. Areas of potential contamination include the area housing the reactor and test items.

d. Pool Research Reactors. Pool reactors are atmospheric pressure, water cooled assemblies generally used to produce long-term or steady-state, low flux thermal neutron radiation. Some pool reactors can also produce high flux thermal neutron radiation for a very short period of time. The neutron radiation is made available for use outside the reactor by beam ports which penetrate the reactor structure. Items to be irradiated are placed in front of the beam ports. Activation of test items, cooling water impurities, and surrounding structures can occur.

(1) Types of Radiation Expected From the reactor, primarily gamma and neutron radiation are expected. Beta and gamma radiation are expected from activated items or activated impurities in the cooling water.

(2) Types of Sources Present. The reactor can be considered a sealed source because the uranium fuel and fission products are contained in cladding. The water and air in the area of the reactor core may become activated and can be considered an unsealed source. Neutron activated test items or reactor structures would be classified as partially sealed radioactive sources. Sealed and partially sealed sources will be present for instrument checks and calibrations.

(3) Radioactive Contamination Potential. There is a moderate potential for contamination in a pool reactor facility. The radioactive material in the cooling water, which results from neutron activation of impurities, is carried through the cooling system and deposits in pipes, valves, pumps, and other system components. Anytime these components are opened for maintenance or repair or if leaks occur, contamination is likely. The coolant radioactive material inventory will be increased if the fuel cladding leaks or is damaged in some manner, releasing fission products into the cooling water. The potential for neutron activation of test items or the structures surrounding a reactor is high.

(4) Radioactive Waste Generated Moderate volumes of solid and liquid radioactive wastes will be produced at this type of facility. In addition, radioactive gases may be present.

(5) Potentially Contaminated Areas. Areas of potential contamination include the following:

(a) Area housing the reactor.

(b) Areas housing reactor auxiliary system.

(c) Test items.

(d) Maintenance areas.

(e) Solid radioactive waste handling and packaging area.

(f) Liquid radioactive waste system (tanks, pumps, valves, piping).

(g) Ventilation system (ducting, filters, filter housings).

(h) Decontamination areas.

e. Power Reactors. The DOD no longer operates power reactors. There are no plans to construct any such facilities in the future. The user of this manual may have need to manage the decommissioning life cycle of an old existing DOD power reactor which has been shut down. For this reason, a limited discussion of radioactive source considerations is provided.

(1) Types of Radiation Expected From the reactor, primarily gamma and neutron radiation are expected. Irradiation of the reactor structures or impurities in the cooling water will result in beta and gamma radiation.

(2) Types of Sources Present. The reactor can be considered a sealed source because the uranium fuel and fission products are contained in cladding. Impurities in the primary system cooling water which become activated can be considered an unsealed source. Any radioactive material resulting from neutron activation of reactor structures would be classified as partially sealed sources. Sealed and unsealed sources will be present and used for instrument checks and calibrations. Radioactive gases may also be present.

(3) Radioactive Contamination Potential. The potential for contamination in a power reactor facility is high. The radioactive material in the primary system cooling water, which results from neutron activation of impurities, is carried through the primary system and deposits in pipes, valves, pumps, the steam generator, and in other primary system components. When these components are opened for maintenance or repair, or if leaks occur, contamination is likely. The primary system radioactive material inventory will be increased if the fuel cladding leaks or is damaged in some manner, releasing fission products into the primary cooling water. The potential for neutron activation of the structures surrounding a reactor is high.

(4) Radioactive Waste Generated Large volumes of solid and liquid radioactive wastes are produced at this type of facility. Radioactive gases may also be present.

(5) Potentially Contaminated Areas. Areas of potential contamination include the following

(a) Area housing the reactor.

(b) Area housing reactor auxiliary systems.

(c) Maintenance areas.

(d) Equipment decontamination areas.

(e) Personnel decontamination areas.

(f) Protective clothing laundry area.

(g) Respiratory protective equipment decontamination area.

(h) Solid radioactive waste handling and packaging area.

(i) Liquid radioactive waste system (tanks, pumps, valves, piping).

(j) Ventilation systems from radioactive gases (ducting, filters, filter housings).

f. Accelerator Facilities. Facilities may include the use of electron linear accelerators (linacs), which are radiation producing machines used for medical and industrial purposes. Other types of particle accelerators are used for physics and medical research. Electron linacs can emit a primary beam of electron radiation (similar to beta) or a secondary beam of X-radiation (X- rays, similar to gamma) for use in radiation therapy. The patient is positioned relative to the output beam port and the machine is energized for the time required to produce the amount of radiation desired for the therapy. Electron linacs are also used in industrial applications to produce X-rays used for the radiography of such items as welds, castings, and munitions. Electron linacs are used in research applications to determine the effects of irradiation on various materials under study. In addition, the electron beam can be used to directly expose the test item. Test items may be exposed to electrons or X-rays.

(1) Types of Radiation Expected At the time of decommissioning neutron activated materials may be present. Radioactive gases may also be present.

(2) Types of Sources Present. The neutron radiation may activate areas of the linac around the output beam port and the structure surrounding the linac. If this occurs, the radioactive material would be considered a sealed source.

(3) Radioactive Contamination Potential. The potential for neutron activation contamination exists, particularly for units operating above 10 MeV.

(4) Radioactive Waste Generated. No liquid or solid radioactive waste is expected unless the electron linac exceeds 10 MeV, in which case very small volumes of solid waste resulting from neutron activation may be produced. Small volumes of radioactive waste may be generated by other types of particle accelerators.

(5) Potentially Contaminated Areas. The surrounding structure and the area around the electron linac output beam port can be contaminated if the output energy is greater than 10 MeV. Special precautions may be necessary for nuclear reactions with low energy thresholds, such as Be-9 and H-2.

g. Radiography Facilities. The primary purpose of radiography facilities is to nondestructively test items for defects. For example, welds are radiographed to reveal any hidden porosity or cracks; castings are radiographed to reveal any hidden voids; aircraft structural components are radiographed to detect early signs of corrosion; and munitions are radiographed to check for proper assembly. Electromagnetic radiation penetrates a test item and exposes a sheet of film in the same manner that light exposes film to produce an image. Radiographic films are processed and checked for defects in the item radiographed. The electromagnetic radiation needed for radiography may be produced by a sealed source of radioactive material such as cobalt-60 or iridium- 192, by X-ray machines, or by electron linear accelerators (para C-4.f.). Sealed radioactive sources must be housed in shielded containers when not in use. The containers may be fixed or portable. X-ray machines require no shielding when not in use because radiation is produced only when a machine is electrically energized. Shielding may be required when a machine is energized. X-ray machines may be installed in a fixed configuration or may be portable.

(1) Types of Radiation Expected Gamma radiation is expected to be encountered during decommissioning from sealed sources. In addition, radiation from test items and structures which have been activated due to exposure to neutrons may be encountered.

(2) Types of Sources Present. Sealed radioactive material and partially sealed neutron activated material can be expected.

(3) Radioactive Contamination Potential. Contamination through spread of radioactive material is not expected for sealed sources unless the source is damaged in a manner which breaches the integrity of the material used to encapsulate the radioactive material, or if the sealed source leaks for any other reason. The potential for neutron activation of materials is present.

(4) Radioactive Waste Generated None is expected except through neutron activation

(5) Potentially Contaminated Areas. None is expected unless exposed to neutrons.

h. Radioluminous Device Storage Facilities. These facilities store new and used radioluminous devices such as clocks, aircraft instruments, and gun sights.

(1) Types of Radiation Expected The radioactive materials primarily used to provide luminosity are tritium, promethium-147, and radium-226. Tritium emits beta radiation only, promethium- 147 emits beta radiation only, and radium-226 emits alpha and gamma radiation. (There will also be beta radiation emitted by the decay products of radium-226 which are also radioactive).

(2) Types of Sources Present. Radioluminous devices are considered partially sealed sources because the radioactive material can usually be exposed easily in a device such as a clock or an instrument.

(3) Radioactive Contamination Potential. Devices containing tritium are subject to leakage so there is a potential for contamination.

(4) Radioactive Waste Generated Any item exposed to tritium contamination may have to be considered radioactive waste.

(5) Potentially Contaminated Areas. Areas can become contaminated from leaking devices. Special precautions are necessary for items exposed to tritium.

i. Depleted Uranium Test and Storage Facilities. Depleted uranium (DU) is used to manufacture various types of munitions and projectiles. These munitions are stored in various facilities and are used in test and practice firings.

(1) Types of Radiation Expected Alpha and gamma radiation can be expected.

(2) Types of Sources Present. The DU in the stored munitions is painted so these sources would be considered partially sealed. In test areas, after the munitions are detonated or projectiles fired into a target, the sources present would be unsealed. Fragments are launched and dust particles of DU are dispersed in the air and eventually settle on surfaces.

(3) Radioactive Contamination Potential. None while the munitions are in storage. After the munitions are fired, there will be contamination of target areas and target materials.

(4) Radioactive Waste Generated None from storage. The DU after firing must be collected and disposed of as waste.

(5) Potentially Contaminated Areas. Firing ranges and targets are areas of potential contamination.